Year: 2017

Comparative analysis of the mechanical properties of fiber and stainless steel multistranded wires used for lingual fixed retention

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Abstract: Objective To evaluate the effect of different resins used for the co-polymerization of EverStick fiber-reinforced fixed orthodontic retainer on its mechanical properties and to compare the mechanical properties of these configurations to commonly used multistrand wires. Materials and methods Ten 0.0175-in. WildCat (WC175), ten 0.0215-in. WildCat (WC215) three-strand twisted wires and thirty EverStick fibers were tested in this study. The EverStcik fibers were equally shared in three groups (n = 10). The samples of first group (ESRE) were polymerized employing Stickresin (Light cure enamel adhesives), the second one (ESFT) employing Flow Tain (Light cured composite), whilst the specimens for the third group (ES) were not combined with resin. All samples were loaded in tensile up to fracture in a universal tensile testing machine and the modulus of elasticity, tensile strength and strain after fracture were recorded. The same groups were also tested employing Instrumented Indentation Testing (IIT) and Martens Hardness (HM), Indentation Modulus (EIT) and elastic index (IT) were determined. The results of tensile testing and IIT were statistically analyzed employing one way Anova and the Student Newman Keuls test (SNK) at a = 0.05 level of significance. Results WC175 and WC215 showed higher modulus of elasticity and tensile strength but lower strain after fracture compared to Everstic groups. IIT illustrated significantly higher values for HM, EIT, and IT for WC groups compared to ESRE, ESFT and ES. ESFT showed higher HM and elastic index compared to ESRE and ES, a finding which is attributed to the fact the FlowTain is a filler-reinforce composite with higher hardness compared to unfilled resins. Significance Multistrand wires demonstrated higher values in mechanical properties compared to EverStick ones. The co-polymerization with difference resins does not affect the tensile properties of Everstic, however the use of a light cured composite has a beneficial effect on hardness.

DOI: https://doi.org/10.1016/j.dental.2017.01.006

Originally published at:
Annousaki, Olga; Zinelis, S; Eliades, G; Eliades, T (2017). Comparative analysis of the mechanical properties of fiber and stainless steel multistranded wires used for lingual fixed retention. Dental Materials, 33(5):e205-e211.
DOI: https://doi.org/10.1016/j.dental.2017.01.006

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Dent Mater. 2017 May;33(5):e205-e211. doi: 10.1016/j.dental.2017.01.006.
Epub 2017 Feb 4.

Abstract

Objective: To evaluate the effect of different resins used for the co-polymerization of EverStick fiber-reinforced fixed orthodontic retainer on its mechanical properties and to compare the mechanical properties of these configurations to commonly used multistrand wires.

Materials and Methods: Ten 0.0175-inch WildCat (WC175), ten 0.0215-inch WildCat (WC215) three-strand twisted wires and thirty EverStick fibers were tested in this study. The EverStcik fibers were equally shared in three groups (n=10). The samples of first group (ESRE) were polymerized employing Stickresin (Light cure enamel adhesives), the second one (ESFT) employing Flow Tain (Light cured composite), whilst the specimens for the third group (ES) were not combined with resin. All samples were loaded in tensile up to fracture in a universal tensile testing machine and the modulus of elasticity, tensile strength and strain after fracture were recorded. The same groups were also tested employing Instrumented Indentation Testing (IIT) and Martens Hardness (HM), Indentation Modulus (E_{IT}) and elastic index (η_{IT}) were determined. The results of tensile testing and IIT were statistically analyzed employing one way Anova and Student Newman Keuls (SNK) at a=0.05 level of significance.

Results: WC175 and WC215 showed higher modulus of elasticity and tensile strength but lower strain after fracture compared to Everstic groups. IIT illustrated significantly higher values for HM, E_{IT}, and η_{IT} for WC groups compared to ESRE, ESFT and ES. ESFT showed higher HM and elastic index compared to ESRE and ES, a finding which is attributed to the fact the FlowTain is a filler-reinforce composite with higher hardness compared to unfilled resins.

Significance: WC groups demonstrated higher values in mechanical properties compared to EverStick ones. The co-polymerization with difference resins does not affect the tensile properties of Everstic, however the use of a light cured composite has a beneficial effect on hardness.

Introduction

Permanent or long term fixed retention is nowadays considered essential in order to maintain stability of the orthodontic result. Bonded retainers on the lingual surface of the mandibular and often the maxillary anterior teeth, combined or not with a removable maxillary plate are routinely used in the orthodontic practice.

There are two main categories of mandibular fixed wire retainers: (a) round, rigid stainless steel wires (0.030-0.032-in) bonded only on the canines and referred to as canine-and canine retainers and (b) canine-to-canine retainers. The latter consist of thin multistranded round wires, or small cross-section rectangular wires bonded to all anterior teeth [1,2]. In addition to the traditional wire retainers, fiber reinforced materials and also alumina ceramic retainers have been alternatively introduced [3-9]. Fiber reinforced retainers have superior aesthetics as the blend with the natural tooth shade, they eliminate the need for working plaster models and they offer a good alternative to wire retainers for patients with Nickel allergy. Some clinicians also find that the placement of fiber reinforced retainers is often a relatively complex and technique sensitive procedure [8].

Ideally a fixed retainer should be easy to apply, passive when bonded, stiff enough to promote stability and at the same time somewhat flexible in order to allow for biological tooth movement. The latter is very important because it helps maintain the periodontal health and at the same time it reduces the stress concentration within the composite [10]. Per definition a more rigid wire will not allow for physiological tooth movement as good as a multistranded wire. However research reports that even a relatively small diameter multistranded wire with six bonding points will impede tooth mobility significantly, with an interindividual variation depending on the shape of proximal contacts, the width and shape of the teeth and the position and size of the bonding points [11] .

The wires used for the construction of fixed retainers can be bend to fit the lingual surface of the anterior teeth and be bonded totally passive. The passivity of the retainer is essential since residual stress in the wire may be expressed on the teeth resulting in alignment irregularities. However an absolutely passive situation can hardly be achieved with the multistranded wires since their flexibility makes them prone to distortion during oral activity [12].

Pullout force tests have shown that the surface characteristics of the wire might affect the retention in the composite matrix [13]. A larger diameter wire with a greater surface area embedded in the adhesive will require a greater force to remove it. Stranded wires offer the advantage of increased surface roughness and contact area. Fiberglass strips are actually soaked in composite and therefore present the largest contact area. In the case of the fiber-reinforced retainers the failure does not come from detachment at the interface between materials but on the contrary from its rigidity. Glass-fibers retainers act like stiff units which resist physiological tooth movement causing eventually fracture of the retainer [13].

Fixed retainers are systems made by a combination of different materials. A fixed wire or fiber-reinforced retainer is bonded to the teeth with adhesive. Adhesive and wire or adhesive and fibers have their own individual mechanical properties, which combined together to create a new system. This system behaves as a unit as long as the elastic limit of its components is not breached and the interface withstands the developed stresses. If the stresses produced by a still active wire are higher than these limits, wire deformation or even rapture at the wire/adhesive interface and consequent breakage of the retainer may occur.

Taken that the retainer has been applied in the mouth under perfect conditions (no saliva or water contamination, passive wires, perfect fit on the teeth) it lies on the properties of its components to determine the resistance and thus the stability of the retaining system. The size of the teeth and the periodontal status, the physical and mechanical properties of the wire and the adhesive and the intraoral biomaterial aging play a critical role for the biomechanical performance of the retainer in the dynamic oral environment [13-16].

The aim of the study was to compare the mechanical properties between fiberglass-reinforced retainers and 3- stranded orthodontic wire retainers. The null hypothesis is that there are not significant differences in mechanical properties among multistranded wires and fiber reinforced composites tested.

Materials and Methods

Tensile testing

Thirty EverStick fibers (G.C Europe, Leuven, Belgium), ten 0.0175’ WildCat (DENTSPLY Int York, PA USA) and ten 0.0215’ WildCat 3-strand twisted wire were tested in tensile testing.

The 30 EverStick fibers were equally divided in three groups of 10 specimens each. The samples of first group (ESRE) were polymerized employing Stickresin (Light cure enamel adhesives) (G.C Europe), the second one (ESFT) employing Flow Tain (Light cured composite, Reliance Orthodontics Products, Itasca, IL)while the specimens for the third group (ES) were polymerized without any resin addition. All samples were polymerized for 40 sec with about 50% overlapping irradiations with a curing unit (Radii plus SDI, Victoria, Australia) emitting at 440~480nm with 1500mW/cm^2 intensity. A short description of groups tested is presented in Table 1.

The diameter of Everstick samples were measured in three different points with a digital micrometer and the mean value was used for tensile properties calculations. However the calculation of tensile properties of multistranded wires requires the estimation of additional geometrical features of wires themselves. Especially for multistranded wires consist of circular wires the diameter of stranded wire (D), the diameter of wire strand (d), the axial displacement per twist of a wire strand (l*) and the helix angle (a) must be calculated. All these features are presented in Fig 1.

A 15-mm section from each wire were placed in an Scanning electron microscope (Quanta 200, FEI, Hillsboro, OR, USA) and secondary electron images were taken under 25KV accelerating voltage, 105μA beam current and 40X nominal magnification. The geometrical features l*, D and d were measured in 10 different locations with the dedicated image analysis software XTDocu (Soft Imaging System GmbH, FEI Company, Hillsboro, OR) and averaged. The helix angle was determined by the formula [17-18]:

$$a = \tan^{-1}\left(\frac{l^*}{\pi(D-d)}\right) \tag{1}$$

Then the modulus of elasticity (E_w) was calculated by the formula for multistranded wires [19] :

$$E_w = \frac{1}{A}\sum_{i=0}^{n} \frac{z_i cos^3(b) E_i A_i}{(1+v_i sin^2(b))} \tag{2}$$

Where z_i is the number of wires, b is the complementary helix angle, A_i,E_i and v_i, the cross section area, modulus of elasticity and Poisson's ratio respectively. The formula was transformed for a 3 stranded wire as follows:

$$E_w = \frac{1}{A}\frac{3cos^3(b)E\pi(\frac{d}{2})^2}{(1+vsin^2(b))} \tag{3}$$

The cross sectional wire area A is given by the equation (Feyner 2007):

$$A = \frac{\pi}{4}\sum_{i=0}^{3} d_i^2 = \frac{3\pi d^2}{4} \tag{4}$$

Combing the last two equations the E_w for a 3 stranded wire is given by the formula

$$E_w = \frac{cos^3(b)E}{(1+vsin^2(b))} \tag{5}$$

According to the manufacturer of WildCat Wire, this wire is made of 3 strand twisted wires made of 304-VAR (Vacuum Arc Remelted ingots) SS with 193 GPa modulus of elasticity and 0.24 Poisson's ratio [20] . Then the wires of each group were grasped using a wire rod tensile grip and loaded in tensile in a universal tensile testing machine (Zwick Line Z2.5, Zwick Roell, Ulm, Germany) with 1mm/min crosshead speed up to fracture. The tensile strength (TS) (determined as the breaking force (maximum force) to cross sectional area A ratio)and elongation (e) after fracture were determined from the tensile strain curves.

Fractography

The fractured surfaces of three wires from WC175 and WC215 groups were imaged in a SEM employing the aforementioned operating conditions in 250 and 2000X nominal magnifications. Fractures samples from the rest groups were photographed with a camera.

Instrumented Indentation Testing (IIT)

Specimens prepared from WildCat 175 and WildCat 215 were cut into 15-mm segments using a low speed oil-cooled diamond saw (IsoMet, Buehler, Lake Bluff, Il). Then the segments were embedded longitudinally in an epoxy resin (EpoFix, Struers, Ballerup, Denmark) and were ground and polished up to 1-μm alumina slurry in a grinding/polishing machine (EcoMet III, Buehler). Fifteen EverStic fibers were randomly divided in three groups (n=5). Each fiber was cut in almost equal parts of 2 mm with a surgical lancet. The fiber of first group were immersed in StickResin (ESRE) of second one in FlowTain (ESFT) while no resin was used in third group (ES). The fibers were aligned together along their long axis and placed between two slabs. The slabs were pressed slightly one against the other and each point was cured for 40 sec as described above.

Force-indentation depth curves were monitored applying 4.9 N with a 2-s dwell time by a Vickers indenter employing an Instrumented Indentation Testing machine ZHU0.2/Z2.5 (Zwick Roell). Five readings were taken from each specimen, and the mean value was used as representative of the specimen. Martens Hardness (HM), Indentation Modulus (E_{IT}) and elastic index (η_{IT}) which represents the ratio of elastic to total indentation work were derived from force-indentation depth curves.

Statistical analysis

The results of tensile testing and IIT were statistically analyzed by one-way ANOVA while significant differences among groups were allocated by post hoc Student- Newman-Keuls (SNK) multiple comparison test at a = 0.05.

Results

SEM analysis of geometrical features of 3-stranded wires

Figure 1 illustrates representativ SE images from the usrface of WC175 and WC215 groups with the geometrical features annotated on the image. Mean values and standard deviations of measured features are appeared in Table 2.

Tensile testing

Figures 2 demonstrates stress strain curves from all groups tested. Interstingly the force displacement curves for EverStic groups showed a long first stage of increased strain under low steady stress. The results of tensile properties and the outcome of statistical analysis are presented in Table 3. WC groups showed much higher modulus of elasticity and tensile stregnth but lower strain after fracture compared to EverStick groups. Signfigcant differences were also allocated for all properties tested between WC175 and WC215 while only ESRS showed higher tensile strength compared to ES.

Fractography

SE images showed that fracture plane is almost perdendicular to the long axis of stranded wires with a rather featureless surface pattern (Figure 3A). However in higher magnification few shallow dimples indicative of tensile overloading were identified (Figure 3B). Figure 3C shows fractured samples from the EverStic groups where the presence of broken fibers is evident.

Instrumented Indentation Testing (IIT)

Representative force indentation depth curves are illustrated in Figure 4A. The higher indentation depth of EverStic groups denotes lower hardness while the steeper unloading curve of SS indicates higher modulus of elasticity. Interestingly the indentation in EverStic groups shows an anisotropic shape with the horizontal diagonal (parallel to fibers) to be smaller compared to the vertical one (vertical to fibers). The results of IIT measurements along with the statistical findings are shown in Table 4.

DISCUSSION

Based on the results of this study the null hypothesis must be rejected as significant differences were identified in mechanical properties among the groups tested. According to the results of geometrical features, WC175 and

WC215 wires share equal axial displacement per twist of a wire strand (l*) but WC215 demonstrated larger diameter of wire (D) and diameter of wire strand (d) following the higher nominal cross section surface of WC125. The latter showed a smaller helix angle in accordance to previous results where the helix angle is decreasing when larger wires are used for the production of multi-strands [17] .

The WC175 wire appeared to have better tensile strength and increased stiffness in comparison to the WC215 wire. A slightly higher modulus of elasticity was calculated for WC175 compare to WC215 based on calculation of equation 5, a finding that is in accordance with the stress-strain curve (Fig 2) where WC175 showed a steeper increase denoting a higher modulus of elasticity. However it must be noted that this value is a rather structure property than a material property as it is depended on geometrical features and thus is better to consider these values more as modulus of stiffness of structure itself. Therefore WC175 is stiffer compared to WC215 per unit of volume of a triple-strand.

WC175 demonstrated also higher tensile strength but lower strain after fracture verifying the trend of previous reports where the tensile strength is decreasing over the thicker wires used [17] . Fractographic analysis (Fig 2A and B) for both WC groups revealed the presence of shallow dimples, which are appended to limited plastic strain after fracture. In general, orthodontic wires are manufactured by cold drawn wires where the ductility is sacrificed for the sake of hardness [21] . Since these wires are made of the same alloy, no significant differences were identified in HM, E_{IT}, and η_{IT} as it was expected. However E_{IT}, was found to be much lower than the nominal value of 193 GPa, a finding which is associated with the limitation of IIT to determine the modulus of elasticity in non-stress free samples because of the implication of residual stresses in the method of estimation of this property [22]. The elastic indices were found similar to previous findings for multistranded wires [21] but higher than the values expected for ductile alloys (<30%) [23]. The latter could be assigned to the limited ductility of cold drawn wires [24].

In our set-up the type of the adhesive used, did not seem to play an important role on tensile properties of groups tested. No significant differences were identified among EverStic groups for modulus of elasticity, tensile strength and strain after fracture denoting that the application of different resin imposes no significant effect on tensile properties. All EverStick groups present a first stage of extended strain almost up to 6% under nominal stresses, a finding which is in agreement with previous findings [25], which might be appended to the extension of elastic resin and/or the straitening of fibers.

The absence of significant differences in tensile properties among groups should be attributed to the fact that fibers are much stronger than the unfilled resin (PMMA + BIS-GMA) [25], and thus they dominate the tensile properties of these retainers while the former is used to keep the fibers together and facilitate appropriate handling. Similarly, IIT showed no significant difference in E_{IT}, as this property is dominated by the mechanical properties of fibers while these values are similar to the ones provided by tensile testing. The higher HM and elastic index of ESFT should be explained by the increased hardening effect of FlowTain, which is a filled resin. The higher elastic index denotes a more brittle material compared to ESRE and ES, which is also attributed to the filled resin.

Flowable composite resins and bracket adhesives, diluted or not, are largely used for the bonding of fixed lingual retainers. Low viscosity composites have the advantage of flowing towards the bulk of the material rather than away from it. This is an important property because it minimizes the need of trimming and accelerates the bonding procedure, which may eventually lead to less risk of failure [26].

The composites used for fixed retainers are constantly exposed to the dynamic, oral environment, thus greatly affected by the intraoral aging mechanisms. Material-hardness is a mechanical property strongly correlated to wear resistance i.e. abrasion via mastication. For the construction of fixed retainers adhesives with increased hardness are preferred. The hardness can be differ with different types of composites and may be altered with manipulation of the product. Diluting resin composited during retainer bonding is affecting (decreasing) the hardness of the material.

The biomechanics of fixed retainers are complex as it involves materials, design and application method as well as geometrical and tissue properties. Depending on the configuration of the retainer (stiff or stranded wire, fiber glass etc), on the type and position of the tooth in the retainer and on the properties of the periodontal ligament, there is a potential for tooth movement as a response to intraoral loading. The elastic properties of the wire and in general the mechanical properties of the retainers are decisive for the expression or the inhibition of these tooth-movements.

Unpredictable tooth movement seems to occur in certain cases even though a fixed retainer is still intact and in position. This applies for a small percentage of patients using multistranded wire retainers and it is usually involving torque differences between adjacent teeth or tooth movements that are not related to the original malocclusion and therefore cannot be considered to be relapse [27]. Wires not totally passive, due to chair-side adjustments, with the objective of achieving better adaptation of the wires to the lingual tooth surface, may induce elastic deformation of the wire with unpredictable effects on its long-term behavior. On the other hand, flexible wires may be deformed plastically by masticatory forces and also fail to resist relapse movement tendencies [28-30].

Whereas the reduced stiffness of the multistranded wires is considered an advantage against more rigid stainless steel wires with respect to physiologic tooth movement, their increased resilience and higher spring-back makes them unreliable in terms of passivity. Low forces may be expressed over longer periods of time due to the increased stored energy in the multistranded wire. Therefore even a perfectly fitting retainer theoretically has the potential to produce forces that if exceeding the periodontal limitations may cause unwanted tooth movement.

The EverStic speciments showed very low modulus of elasticity and hardness. The tensile strength of the EverStic group was also low with only the ESRS giving a better value in comparison with the ES group. The increased strain of the EverStic under low, continuous stress implies that this material reacts to relatively low forces. Tooth mobility at the end of the orthodontic treatment and at the time of placement of the retainers is relatively high [31] meaning that a fiber-reinforced retainer will be very rapidly under increased strain [8].

When applying the fibers to the teeth the interdental areas are splinted by composite. Also the contact area between retainer and tooth surface is very large in comparison to the contact points of a wire retainer. The whole system functions as a rigid splint inducing high strain levels in its mass under loading. When these strain levels exceed the strength of the material, deterioration begins and microcraks form, which will eventually lead to loosening or breakage of the splint/retainer [8]. Literature gives significantly higher failure rates for glass-fiber reinforced compared to multistranded wire retainers (49% vs 88%) [8] and some authors suggest that the use of fiber retainers should be generally discouraged [12].

Conclusions

Three stranded wires demonstrated higher mechanical properties compared to fiber retainers.

The application of different resins has no effect on tensile properties of EverStick group but hardness is enhanced when filled resins are used for co-polymerization with EverStick fibers.

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Table 1. Short description of different groups included in this study.

Group	Short description
WC175	3-stranded wires with 0.0175' nominal cross section
WC215	3-stranded wires with 0.0215' nominal cross section
ESRE	EverStick co-polymerized using the StickResin provided by the manufacturer
ESFT	EverStick co-polymerized using the FlowTain light cure composite
ES	EverStick irradiated without any additional resin

Table 2. Mean values and standard deviations in parentheses of geometrical features measured (n=10).

Group	l* (mm)	D (mm)	d (mm)	a (degrees)
WC175	2.03(0.02)	0.40(0.01)	0.20(0.00)	69.9(0.5)
WC215	2.00(0.01)	0.50(0.01)	0.25(0.00)	64.9(0.6)

Table 3. Mean values and standard deviations in parentheses of tensile properties tested.

Group	Elastic Modulus* (GPa)	Tensile Strength (MPa)	Strain after fracture (%)
WC175	164	1814(44)^{a}	2.9(0.3)^{a}
WC215	151	1726(25)^{b}	4.0(0.3)^{b}
ESRS	6.9(1.9)^{a}	651(47)^{c}	14.6(1.7)^{c}
ESFT	6.0(1.7)^{a}	593(40)^{c,d}	17.2(1.5)^{c}
ES	5.2(1.5)^{a}	543(42)^{d}	16.0(2.6)^{c}

*Elastic modules of WC175 and WC215 were calculated based on equation (5).
Same superscripts denote mean values without statistical significant differences ($p>0.05$)

Table 4. Mean values and standard deviations in parentheses of Martens Hardness, Indentation modulus and elastic index of all groups tested.

Group	HM (N/mm^2)	E_{IT} (GPa)	η_{IT} (%)
WC175	2182(54)^{a}	34.9(0.5)^{a}	58.1(0.4)^{a}
WC215	2205(63)^{a}	35.2(0.3)^{a}	57.9(0.6)^{a}
ESRE	162(9)^{b}	4.9(0.4)^{b}	30.2(1.6)^{b}
ESFT	211(24)^{c}	4.8(0.8)^{b}	41.0(7.9)^{c}
ES	157(6)^{b}	4.7(0.3)^{b}	31.2(2.1)^{b}

Same superscripts denote mean values without statistical significant differences ($p>0.05$)

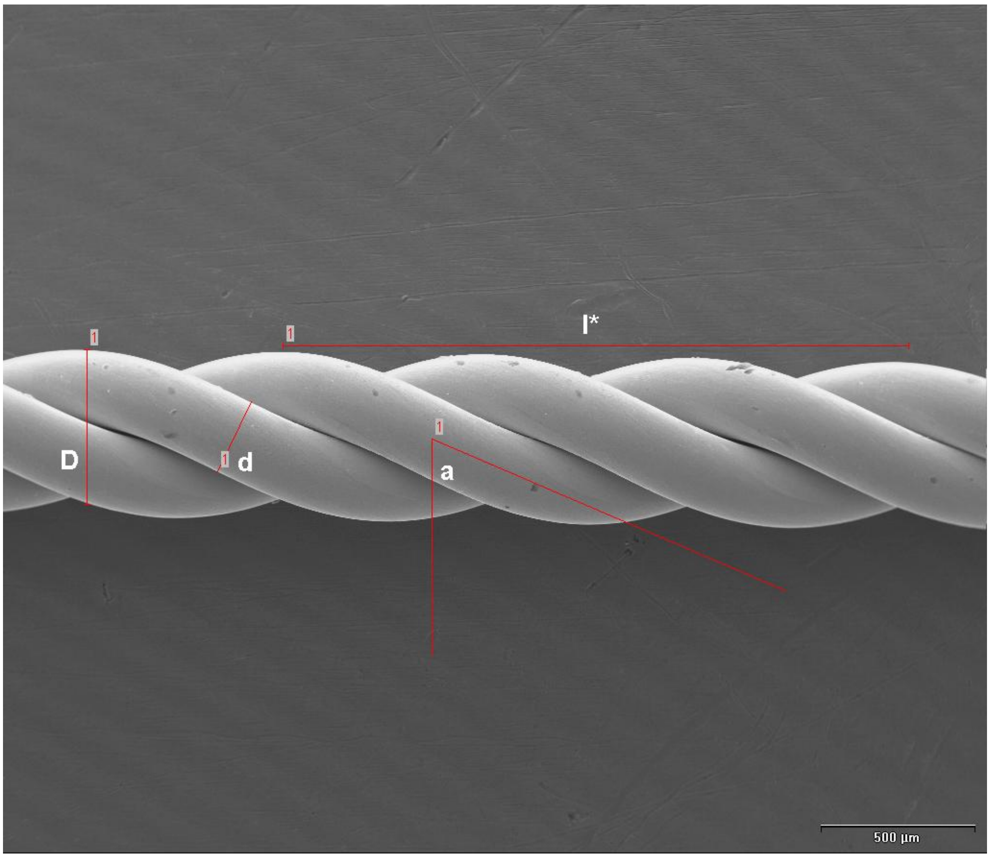

Figure 1. Secondary electron image showing the geometrical features of a multistrand wire. (D) is diameter of wire, (d) is the diameter of wire strand, (l*) the axial displacement per twist of a wire strand and (a) is the helix angle (Scale 500µm).

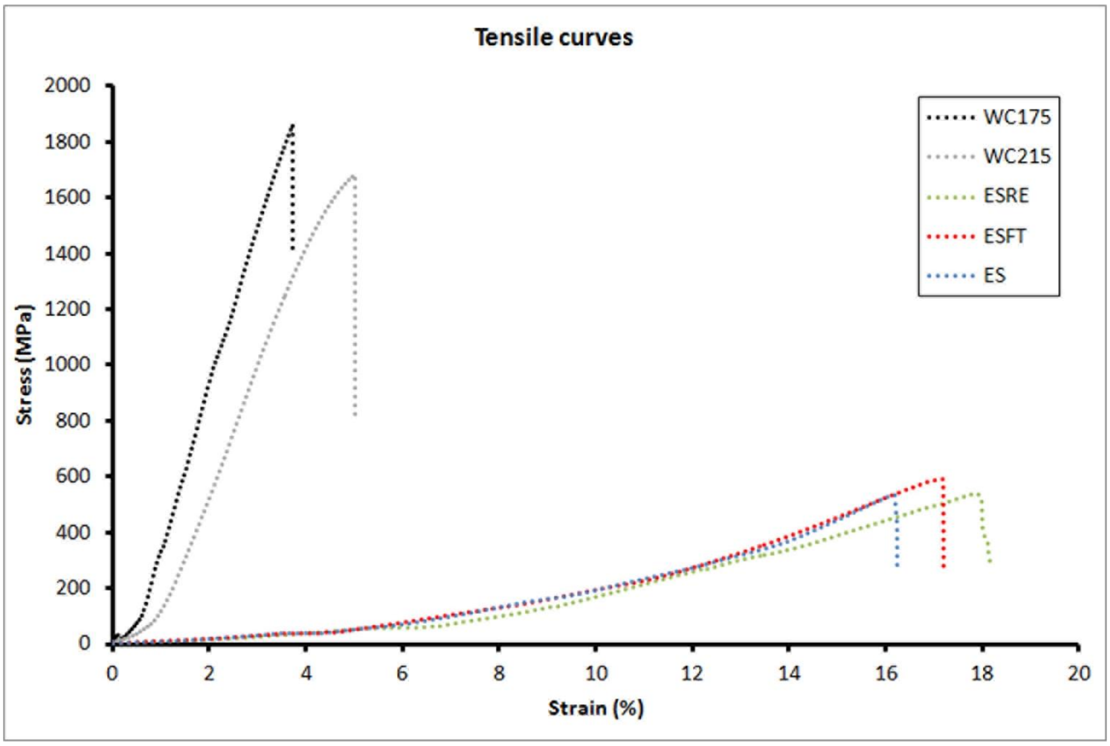

Figure 2. Representative tensile curves for all groups tested.

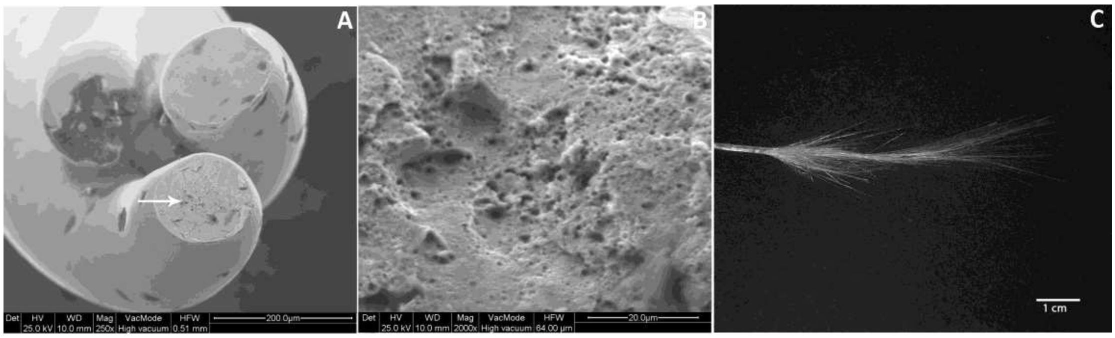

Figure 3. A) Representative SE image from the fracture surface of WC175 and WC215 groups. The fracture surface seems perpendicular to the long axis of wires (nominal magnification 250X). B) Higher magnification of the central region of the lower wire (pointed by arrow) where shallow dimples are appeared (nominal magnification 2000X). C) Representative optical image of broken EverStic sample after tensile testing where the broken fibers are evident.

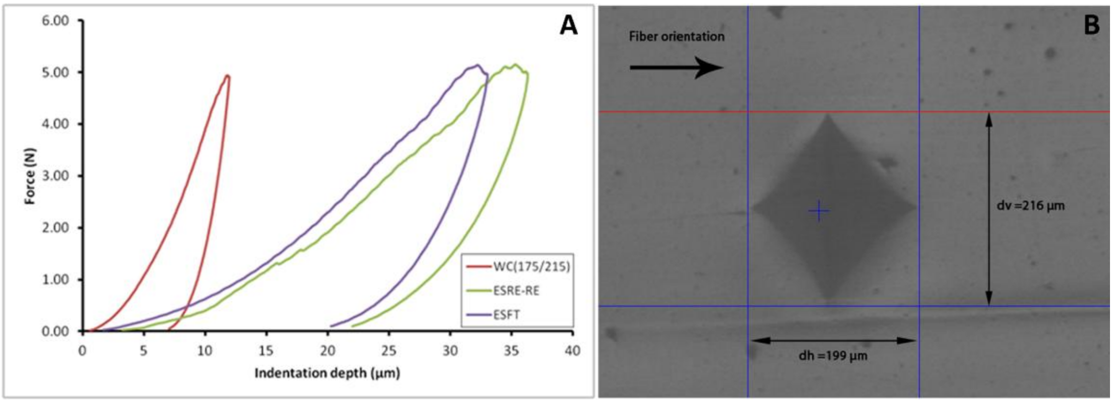

Figure 4. A) Representative force indentation depth curves from all groups tested. B) Figure 8 illustrates an indentation from the EverStick groups where the vertical diagonal is larger than the horizontal one due to the fiber orientation denoting the anisotropic nature of mechanical properties of fiber reinforced material.